



Solar Thermal Collector Component for High-resolution Stochastic Bottom-up Domestic Energy Demand Models

Paul HENSHALL, Eoghan MCKENNA, Murray THOMSON, Philip EAMES

Centre for Renewable Energy Systems Technology (CREST), School of Electronic, Electrical and Systems Engineering, Loughborough University, LE11 3TU, UK. e.j.mckenna@lboro.ac.uk

High-resolution stochastic 'bottom-up' domestic energy demand models can be used to assess the impact of low-carbon technologies, and can underpin energy analyses of aggregations of dwellings. The domestic electricity demand model developed by Loughborough University has these features and accounts for lighting, appliance usage, and photovoltaic micro-generation. Work is underway at Loughborough to extend the existing model into an integrated thermal-electrical domestic demand model that can provide a suitable basis for modelling the impact of low-carbon heating technologies. This paper describes the development of one of the new components of the integrated model: a solar thermal collector model that provides domestic hot water to the dwelling. The paper describes the overall architecture of the solar thermal model and how it integrates with the broader thermal model, and includes a description of the control logic and thermal-electrical equivalent network used to model the solar collector heat output.

Keywords: Solar thermal collector, domestic, energy demand, dynamic.

1. INTRODUCTION

Urban areas currently use over two-thirds of the world's energy and account for over 70% of global greenhouse gas emissions (International Energy Agency 2008). Furthermore, increasing urbanisation means that the proportion of the population living in urban areas is expected to rise from around 50% today to more than 60% in 2030, with urban energy use and emissions expected to rise as a consequence. With deep and binding carbon reduction targets in place in many nations (UK Government 2008, European Commission 2010), the urban environment has therefore become a critical area of focus for addressing the trilemma of secure, affordable and sustainable energy.

Accordingly, there is increasing research interest in urban energy and carbon modelling tools that quantify the economic and environmental impact of urban areas and low-carbon technological and behavioural interventions (Keirstead, Jennings et al. 2012). By helping to understand the energy-use of urban areas better, and providing an evidence-base for improving their performance, such models have the potential to detail the pathways to achieve significant carbon reductions.

The high-resolution 'bottom-up' domestic electricity demand model developed by Loughborough University accounts for electricity consumption and generation associated with domestic appliances, lighting and PV (Richardson, Thomson 2013) and can serve as a basis for urban energy modelling, particularly with a focus on quantifying the impacts of low-carbon technologies on low-voltage distribution networks (Richardson 2010). The model has been used widely within academia and industry (Navarro, Ochoa et al. 2013, EA Technology 2012, Collinson 2014), and work is underway at Loughborough to extend the existing model into an integrated thermal-electrical domestic demand model that can provide a suitable basis for modelling the impact of low-carbon heating technologies. This paper describes the development of one of the new components of the integrated model: a solar thermal collector model that provides domestic hot water to the dwelling. The integrated thermal-electrical demand model will be described elsewhere in forthcoming publications. The following sections describe the type of solar thermal system to be modelled, the thermal-electrical circuit analogy used to model the useful heat output of the system, how the solar thermal component integrates with the broader integrated domestic demand model, the model output calibration and validation, and finally a discussion of future work.

2. DOMESTIC SOLAR THERMAL COLLECTOR SYSTEMS

Domestic solar thermal systems are an example of low-carbon technology that will partially offset electricity and natural gas consumption for the hot water/heating requirements of a dwelling. There are a variety of solar thermal collectors available commercially for domestic purposes. Typically such collectors are either flat plate or evacuated tube varieties of solar thermal collector (Henshall, Moss et al. 2014). Advances in materials over the years has led to improvements in the collection efficiency and thermal insulation of these collectors thus making them more attractive for both the domestic and industrial process heat markets. This is especially the case for installation of such solar thermal collectors in locations of relatively variable climate, such as the UK. For example, recent research at Loughborough University is attempting to utilise a vacuum enclosure to thermally insulate a flat plate solar thermal collector. This would result in a flat plate collector that could reach higher temperatures at higher installed latitudes in comparison to conventional collectors.

The thermal energy generation from such systems is dependent on the variation of local external environmental factors, while thermal energy demand depends partly on the presence and activity of occupants. Generation of solar thermal energy will usually be greatest at solar noon while demand for hot water and heating is likely greatest in the morning and in the evening. This mismatch in generation and demand is buffered via the presence of local thermal energy storage systems, such as hot water cylinders. Accounting for these factors in the developed model is therefore important and will be accounted for as described in following sections.

One can expect the generation of solar thermal energy and the demand for hot water to be somewhat spikey in nature. Subsequently, it is useful to simulate the daily operation of such systems at high temporal resolution and with a common depiction of external irradiance and temperature with regard to generation and occupant activity. Loughborough's existing models produce simulation output at a resolution of 1-minute, and this will also be adopted for the solar thermal collector model described here.

Figure 1 shows the basic integration of a solar thermal collector with a dwellings hot water cylinder. A solar thermal collector is connected to a hot water cylinder via pipes which allow the circulation of a heat transfer fluid between the two components. The heat transfer fluid is typically water, mixed with an anti-freeze, and a pump enables the circulation of the fluid through the pipes. In the model, the pump controller monitors the temperature of the solar thermal collector and the hot water cylinder. If the temperature difference between the collector and the cylinder is greater than 2°C and the cylinder is above a maximum allowed temperature (70°C here) then the controller will turn the pump on and thermal energy will be added to the tank from the collector. If the temperature of the collector falls to within 2°C of the cylinder temperature or the maximum allowed cylinder temperature is exceeded, then the controller will turn the pump off. In the current model it is assumed that there is a perfect heat exchanger within the cylinder such that all the heat contained in the circulating fluid is transferred from the collector to the cylinder.

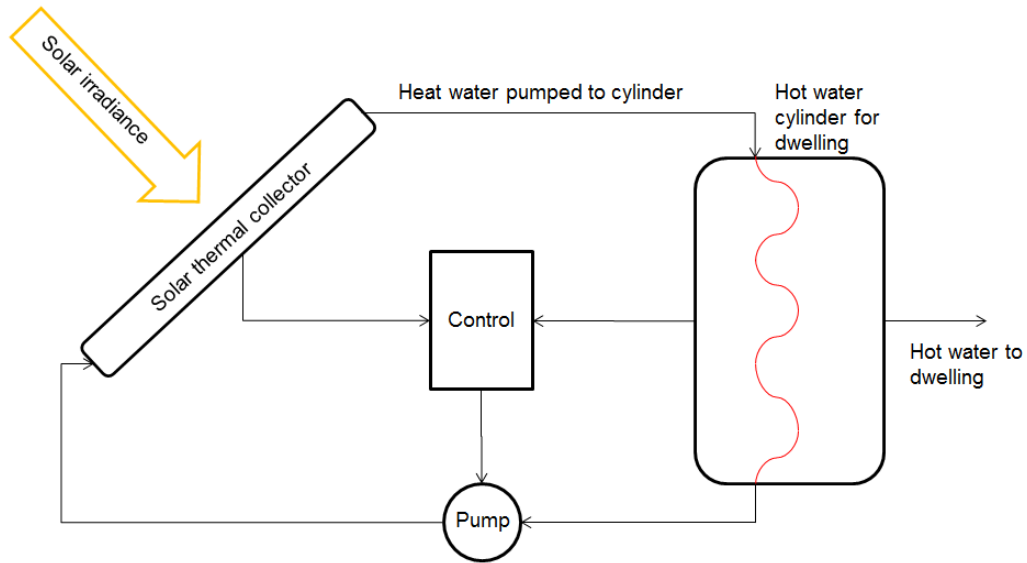


Figure 1: Block diagram of physical system for dwelling.

3. SOLAR THERMAL COLLECTOR COMPONENT MODEL

Stochastic high-resolution ‘bottom-up’ domestic integrated thermal-electric demand models utilise a thermal-electric analogy networks for modelling the behaviours of the various systems (thermal emitters, hot water cylinder heater, etc...) of each dwelling (Good, Zhang et al. 2015, Cooper 2013). It is also common to use such an analogy when modelling the output of solar thermal collectors (Duffie, Beckman 1980, de Vries, Francken 1980, Sproul, Bilbao et al. 2012). The thermal-electric analogy network for the solar thermal collector system used in the model is presented in Figure 2.

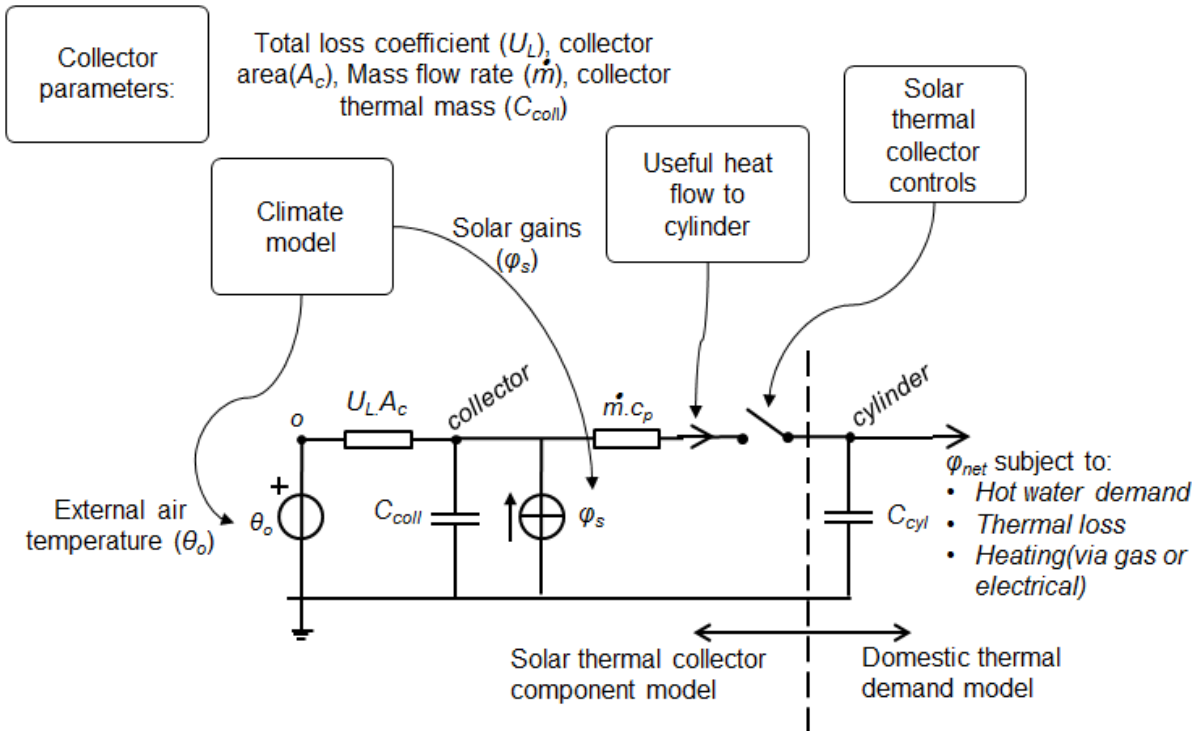


Figure 2: Thermal-electric equivalent network for an individual solar thermal collector and hot water cylinder.

In Figure 2, it can be seen that the model consists of a series of thermal-electric equivalent components such that:

- A node represents a part of the system represented in the model (units: K)
- A resistor represents a heat transfer coefficient between two nodes (units: W/K)
- A capacitor represents a thermal capacitance (units: J/K)
- A voltage source represents a source of constant temperature
- A current source represents a source of thermal power (W)

The thermal-electric equivalent network shown in Figure 2 is relatively simple in that it represents the temperature of components such as the collector and hot water cylinder via a single node with an attached capacitor. This level of simplicity is necessary such that the integrated “bottom up” model can use the solar thermal component to simulate a large number of dwellings quickly. However, despite the reduced order nature of the solar thermal collector model it will be shown to be a reasonable representation of actual solar thermal systems. More complex thermal-electrical network equivalents for modelling solar thermal collectors can be found in the following literature (de Vries, Francken 1980, Sproul, Bilbao et al. 2012).

In the thermal-electrical network depicted in Figure 2, there are two unknown temperatures to be solved for a given simulation time-step; these being the collector node and the cylinder node. Performing an energy balance at each of the nodes provides the equations to be solved during each time step:

Equation 1: Energy balance equation on collector node

$$\dot{\theta}_{coll} C_{coll} = \varphi_s A_c - U_L A_c (\theta_{coll} - \theta_0) - \dot{m} c_p (\theta_{coll} - \theta_{cyl})$$

Where:

- A_c = collector area (m^2)
- C_{coll} = thermal mass of collector (JK^{-1})
- c_p = specific heat capacity of heat transfer fluid ($JK^{-1}kg^{-1}$)
- \dot{m} = mass flow rate ($kg s^{-1}$)
- U_L = total collector loss coefficient ($WK^{-1}m^{-2}$)
- θ_{coll} = collector temperature (K)
- θ_{cyl} = cylinder temperature (K)
- θ_0 = outside temperature (K)
- φ_s = solar gain (Wm^{-2}) = local solar irradiance (I) \times collector transmission-absorption product ($\tau\alpha$)

Equation 2: Energy balance equation on cylinder node

$$\dot{\theta}_{cyl} C_{cyl} = \dot{m} c_p (\theta_{coll} - \theta_{cyl}) - \varphi_{net}$$

Where:

- C_{cyl} = thermal mass of cylinder (JK^{-1})
- φ_{net} = net heat flow from cylinder subject to demand, cylinder heat losses and gain from primary heating system

In the case of the cylinder, Equation 2 utilises a net heat flow (φ_{net}) to describe when it gains heat from an electrical (or gas) heater but also loses heat to the internal environment of the dwelling and when there is a demand for hot water. It should be noted that because the hot water cylinder temperature is represented as a single node, this model considers the hot water cylinder as fully mixed rather than stratified. In the model Equation 1 and 2 are solved via Euler integration. With the inclusion of the thermal mass of the collector in Equation 1 the model can provide an estimate of the dynamic behaviour of the solar thermal collector; this was deemed necessary to provide greater accuracy as the integrated model utilises high temporal resolution data.

As might be expected, as the thermal mass of a collector tends to zero, or the time step of the simulation tends to infinity, Equation 1 will tend to a steady state equation (Equation 3) with a similar form to the well-known Hottel-Whillier-Bliss equation (Duffie, Beckman 1980), such that:

Equation 3: Steady state energy balance equation on collector node

$$\dot{m} c_p (\theta_{coll} - \theta_{cyl}) = A_c (\varphi_s - U_L (\theta_{coll} - \theta_0))$$

4. MODEL ARCHITECTURE AND COMPONENT INTEGRATION

A stochastic multi-dwelling domestic integrated thermal-electrical energy demand model is a collection of smaller components/models that work together to provide specific and aggregated energy demand data for a user specified number of dwellings. Based on historical climate data, occupancy/activity probability distributions and user specified control states the model generates multiple instances of dwellings for which presence and activity of occupants is stochastically calculated with each instance exposed to the same environmental conditions (Richardson, Thomson 2013, McKenna, Krawczynski et al. 2015). Based on the activity, calculations are performed to determine thermal and electrical energy required of each dwelling. This is then aggregated to provide electricity, gas and water demand for the group of dwellings.

A simple depiction of how the solar thermal component integrates with a thermal domestic energy demand model architecture is shown in Figure 3. A climate model provides solar irradiance and outside temperature data to the solar thermal model. In this paper the solar irradiance part of the climate model is the same model developed by Richardson and Thomson (Richardson, Thomson 2013) for the purpose of simulating electrical demand in dwellings with photovoltaic panels. The solar thermal collector model calculates useful heat gain based on the cylinder temperature of the dwelling. The temperature of the cylinder will be dependent on other components within the domestic demand model e.g. heat input from primary heating systems, losses to the indoor air, and domestic hot water draws. The useful heat gain from the solar thermal collector will partially offset energy demand associated with the dwelling's primary heating system e.g. gas demand, allowing the economic and environmental impact of the solar thermal collector to be evaluated.

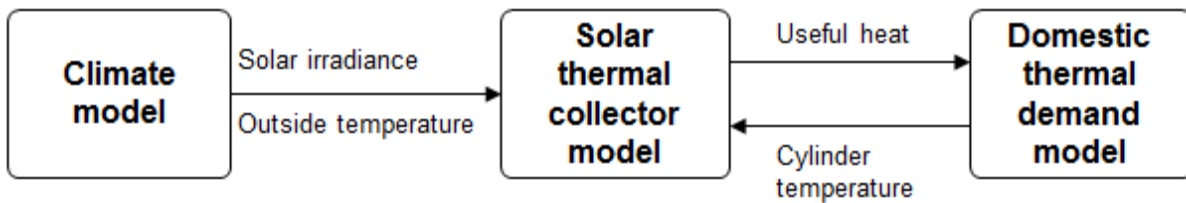


Figure 3: Simple domestic thermal energy demand model architecture.

5. CALIBRATION AND VALIDATION

To calibrate this model and ensure a representative output from the simulated collector, the physical characteristics of a commercial flat plate solar thermal collector were identified or otherwise estimated and are listed in Table 1. The collector area, pump mass flow rate, transmission-absorption product, and collector efficiency slope coefficient are based on a commercial flat plate solar thermal collector datasheet (Kingspan 2015). The heat removal factor is estimated based on a typical value from (Duffie, Beckman 1980). The total loss coefficient is then calculated as the collector efficiency slope coefficient divided by the heat removal factor. Finally, the effective thermal mass of the collector is estimated from (Hellstrom, Adsten et al. 2003).

Table 1: Characteristics of flat plate solar thermal collector for the solar thermal component model calibration

Characteristic	Value
Collector Area (A_c) (m^2)	2
Collector efficiency slope coefficient (k_1) ($WK^{-1}m^{-2}$)	3.73
Pump mass flow rate (\dot{m}) (kgs^{-1})	0.03
Transmission-absorption product of collector ($\tau\alpha$)	0.87
Heat removal factor (F_R)	0.86
Total loss coefficient (U_L) ($WK^{-1}m^{-2}$)	4.34
Effective thermal mass of collector (C_{coll}) ($kJK^{-1}m^{-2}$)	7.5

From the characteristics listed in Table 1 a constant solar illumination test was run on a flat plate solar thermal collector circulating water to a 100 litre capacity hot water cylinder. The efficiency of the collector during the simulation was determined as the ratio of the useful heat flow to the cylinder to the product of the collector area (A_c) and the local solar irradiance (I). It should be noted the total loss coefficient (U_L) is considered constant for the solar thermal collector, which will result in a linear efficiency profile. The linear efficiency of the simulated collector was compared to the linear steady state efficiency reported for the commercial flat plate solar thermal collector (Figure 4). It will be the subject of future work to account for changes in U_L , this will be especially important for the consideration of high temperature solar thermal collector systems. The efficiency of the solar collector decreases as temperature of the cylinder increases as seen in Figure 4. The constant illumination simulation output of the flat plate solar thermal collector demonstrates a consistent behaviour to that of the commercial solar thermal collector. The constant illumination simulation demonstrates a relatively steady state response of the model, however, with dynamic illumination of the collector there will likely be a departure from this behaviour.

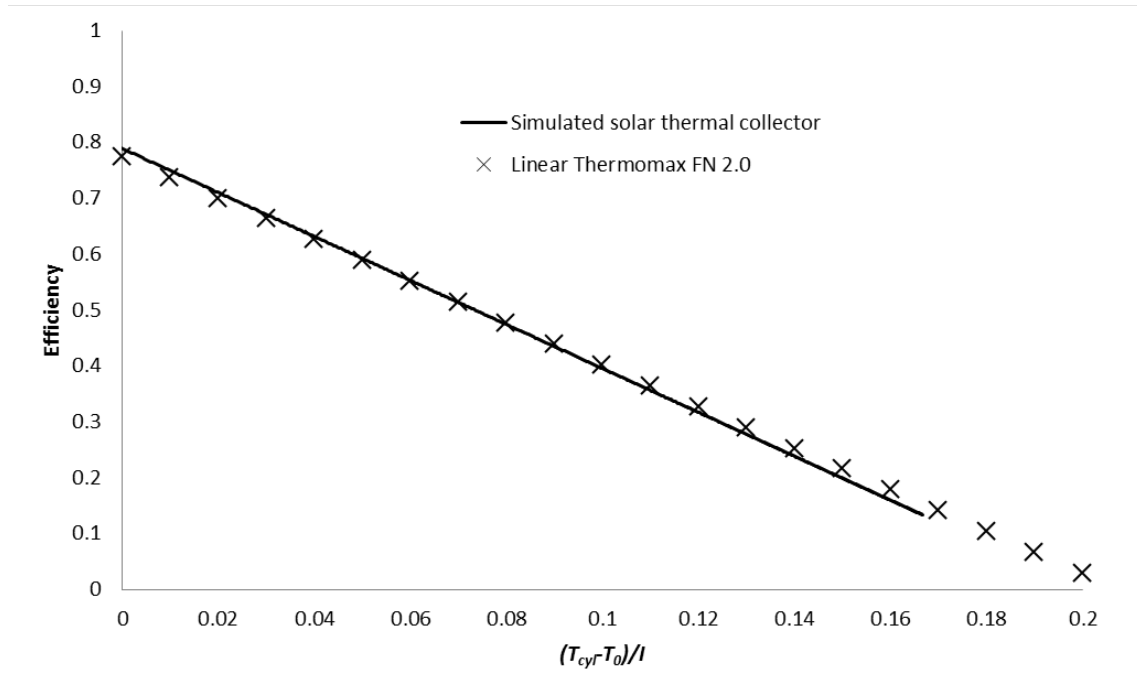


Figure 4: Linear efficiency of simulated and actual flat plate solar thermal collector

6. EXAMPLE OF DYNAMIC SIMULATION OUTPUT

The output from an example dynamic simulation of the solar thermal collector for an individual dwelling subjected to stochastically generated solar irradiance is seen in Figure 5 and 6. In this example the hot water cylinder is subject to a small but constant demand over the course of the day, equivalent to the UK household average of 122 litres / day. Figure 5 depicts the solar power incident on the dwellings solar thermal collector over the course of a day. The incident solar power is generated stochastically using the model developed by Richardson and Thomas (Richardson, Thomson 2013). Also shown in Figure 5 is the useful thermal energy flow from the collector to the hot water cylinder. Figure 6 depicts the temperature variation of the hot water cylinder, the solar thermal collector and the outside air temperature. The presence of the horizontal line in Figure 6 indicates when the pump is on and heat transfer fluid is circulating between the solar thermal collector and the cylinder.

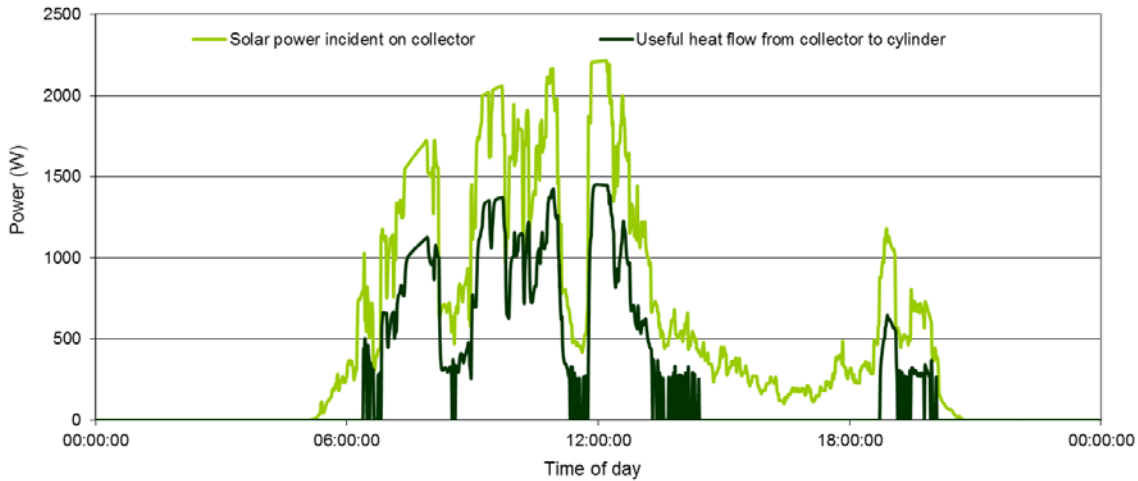


Figure 5: Solar irradiance on collector and useful heat flow from collector to cylinder

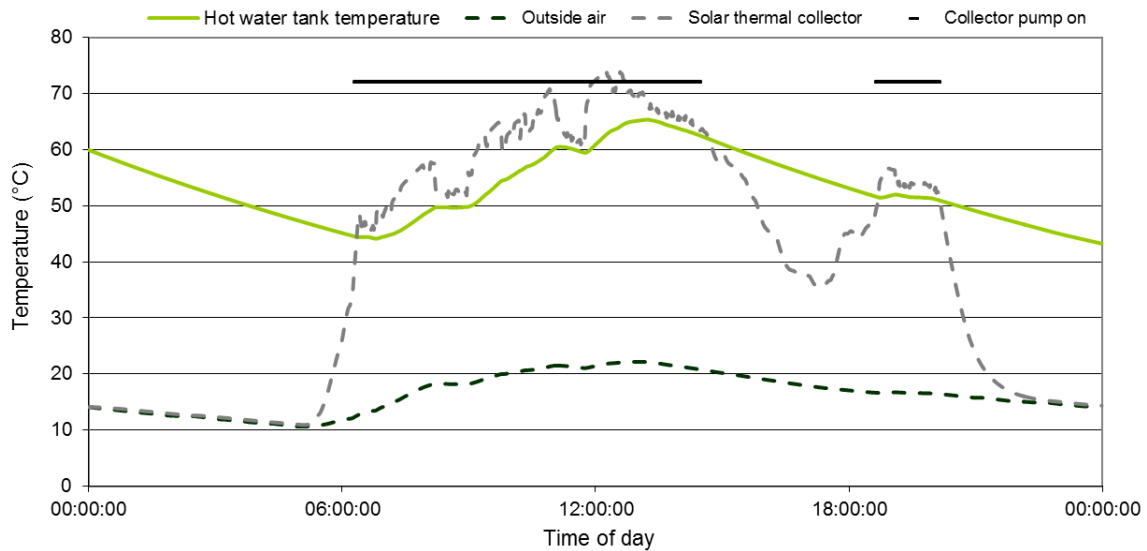


Figure 6: Variation of simulation node temperatures

In Figure 7 the instantaneous efficiency of the output of the solar thermal collector for the day shown above is plotted along with the steady state linear efficiency taken from the collectors data sheet (Kingspan 2015). It can be seen that for continuous operation the simulated collector behaves in a manner consistent with that of the steady state linear behaviour of the commercial collector. However, as to be expected there are instances when the instantaneous efficiency will depart from the linear trend, for example when the collector is heating up or cooling down.

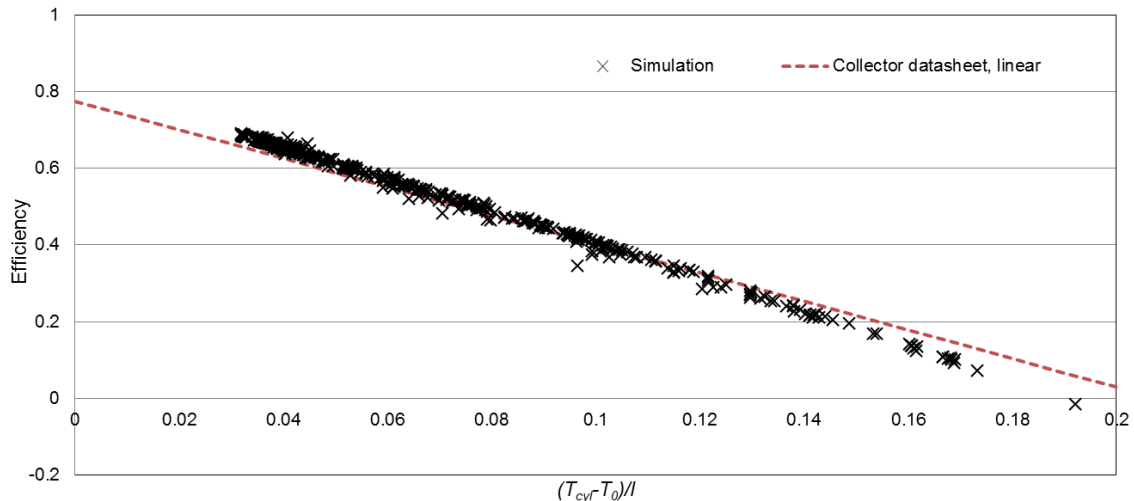


Figure 7: Instantaneous efficiency of simulated collector

7. FUTURE WORK

Future work will focus on publishing the open-source integrated thermal-electrical demand model with solar thermal component. This will allow the application of the model to evaluate the economic and environmental impact assessment of solar thermal systems and inform the extent to which they can contribute to a low-carbon urban environment. The solar thermal collector component will also be improved and extended to include more examples of solar thermal collector systems e.g. evacuated tube and evacuated flat plate, solar thermal for space heating, stratified hot water cylinders and systems with phase-change material storage buffers.

8. CONCLUSION

This paper described a simple linear solar thermal collector component model for use within stochastic multi-dwelling integrated thermal-electrical demand models to assess the large scale impact of domestic solar thermal systems. The model employs a linearized thermal-electric network analogy to calculate the instantaneous heat flow from the collector to a hot water cylinder simulated in an integrated thermal-electrical energy demand model. The simple nature of the model allows it to be utilised to quickly generate high temporal resolution data for a large number of dwellings, expediting the assessment of the impact of a variety of solar thermal collector technologies.

The integration of the solar thermal collector component into the larger model is described, detailing the inputs and outputs required. An example calibration and validation is performed based on the characteristics of an existing flat plate solar thermal collector. The solar thermal collector component model demonstrates behaviour consistent with the linear efficiency profile of the commercial solar thermal collector. Furthermore, the solar thermal collector component model is demonstrated responding to stochastically generated, high temporal resolution solar irradiance data. The solar thermal collector component again demonstrates a response consistent with the commercial collector. Subsequently, the solar thermal collector component model described is considered as a valid tool for use within stochastic multi-dwelling integrated thermal-electrical demand models. With further improvement to the component models accuracy and versatility it is expected to provide useful and representative data for domestic thermal energy demand simulations. Such simulations will help inform how current and future solar thermal technologies will impact domestic energy demand.

9. ACKNOWLEDGEMENTS

This project was supported by the Engineering and Physical Science Research Council within the High Performance Vacuum Flat Plate Solar Thermal Collector for Hot Water and Process Heat project (EP/K009230/1) and the Transformation of the Top and Tail of Energy Networks project (EP/I031707/1).

10. REFERENCES

- COLLINSON, A., 2014. LV Network Management – A Challenge for Network Designers. SP Networks. Presentation given at LCNF Conference Brighton November 2013. Accessed 23 May 2014. .
- COOPER, S., 2013. Thermodynamic Analysis of Air Source Heat Pumps and Micro Combined Heat and Power Units Participating in a Distributed Energy Future (Thesis). Accessed 6 May 2014.
- DE VRIES, H.F.W. and FRANCKEN, J.C., 1980. Simulation of a solar energy system by means of an electrical resistance network. *Solar Energy*, **25**(3), pp. 279-281.
- DUFFIE, J.A. and BECKMAN, W.A., 1980. *Solar engineering of thermal processes*. Wiley New York etc.
- EA TECHNOLOGY, 2012. Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks. Accessed 23 May 2014. .
- EUROPEAN COMMISSION, 28 Jan 2010, 2010-last update, Climate change: European Union notifies EU emission reduction targets following Copenhagen Accord. Accessed on 10th December 2012 [Homepage of Europa], [Online]. Available: <http://europa.eu/rapid/pressReleasesAction.do?reference=IP/10/97&format=HTML&aged=0&language=EN&guiLanguage=en> [27 Oct 2010, 2010].
- GOOD, N., ZHANG, L., NAVARRO-ESPINOSA, A. and MANCARELLA, P., 2015. High resolution modelling of multi-energy domestic demand profiles. *Applied Energy*, **137**(0), pp. 193-210.
- HELLSTROM, B., ADSTEN, M., NOSTELL, P., KARLSSON, B. and WACKELGARD, E., 2003. The impact of optical and thermal properties on the performance of flat plate solar collectors. *Renewable Energy*, **28**(3), pp. 331-344.
- HENSHALL, P., MOSS, R., ARYA, F., EAMES, P.C., SHIRE, S. and HYDE, T., 2014. An evacuated enclosure design for solar thermal energy applications, Grand Renewable Energy 2014 (GRE2014) International Conference and Exhibition, 27 July - 1 August 2014, © Grand Renewable Energy, pp. 4.
- INTERNATIONAL ENERGY AGENCY, 2008. *World Energy Outlook*. Accessed on 10th December 2012. Paris, France: IEA.
- KEIRSTEAD, J., JENNINGS, M. and SIVAKUMAR, A., 2012. A review of urban energy system models: Approaches, challenges and opportunities. *Renewable and Sustainable Energy Reviews*, **16**(6), pp. 3847-3866.
- KINGSPAN, 2015. Thermomax FN 2.0 Datasheet.
- MCKENNA, E., KRAWCZYNSKI, M. and THOMSON, M., 2015. Four-state domestic building occupancy model for energy demand simulations. *Energy and Buildings*, **96**(0), pp. 30-39.
- NAVARRO, A., OCHOA, L.F., MANCARELLA, P. and RANGLES, D., 2013. Impacts of photovoltaics on low voltage networks: A case study for the North West of England, Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on 2013, pp. 1-4.
- RICHARDSON, I., 2010. *Integrated High-resolution Modelling of Domestic Electricity Demand and Low Voltage Electricity Distribution Networks* (PhD Thesis), Loughborough University.
- RICHARDSON, I. and THOMSON, M., 2013. Integrated simulation of photovoltaic micro-generation and domestic electricity demand: a one-minute resolution open-source model. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **227**(1), pp. 73-81.
- SPROUL, A., BILBAO, J. and BAMBROOK, S., 2012. A novel thermal circuit analysis of solar thermal collectors, 50th Annual Conference of the Australian Solar Energy Society 2012.
- UK GOVERNMENT, 2008. *Climate Change Act 2008*. London, UK: .